ANALYSIS OF PROPAGATION OF COMPLEX FIRE: CASE OF *THE YARNELL HILL FIRE 1*

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ABSTRACT

We examine the propagation of the Yarnell Hill Fire in Arizona, June 28 -- July 3, 2013 to assess the nature of its complexity. We identify the critical fire growth that starts about 35 hours after the fire initiation. In a time span of three hours, the fire area is doubled. Within the following four hours, the direction of fire turns by about 180 degrees. An hour later, a pyrocumulonimbus cloud is observed above the fire area. To monitor complex fires, we propose implementation of an IR instrument to scrutinize fire remotely for behaviors, such as vortices and rotation, arising from combustion events, terrain characteristics, and outside influences. We propose a small reconnaissance plane circling to the side and above the fire area to search for anomalies in fire propagation and atmosphere during the fire consolidation during the initial 45 hours. Ideally, the observing instrument would be sensitive in IR region at about 4.5 microns where carbon oxide emits and water transmits the radiation.

Keywords: wild fires, fire propagation, combustion, environmental, fire, plume, carbon dioxide imaging, infrared

1. INTRODUCTION

Wild-land fires may be considered a natural phenomenon, having taken place as a consequence of lightening for at least the last few millennia. Their rejuvenating function is to clear underbrush and destroy sick vegetation. The combustion by-products provide nutrients to the new healthy vegetation growth. In the past 100 years, humans have interfered with fire cycles and encroached on the wild lands.

This shift in dwelling distribution requires an updated control and plan for management of wild fires. In the US southwest, the fire threat is consistently high, starting in springtime, lasting through the fall. Low levels of precipitation, existence of chaparral, high Sonoran desert vegetation, and reportedly highest temperatures on record for the past two consecutive years enhance probability of naturally-initiated fires. Raging wild fires have been reported in Canada, southern, southwestern and western USA, Australia, and other possibly less publicized areas. In recent years, the lack of understanding of the fire initiation and propagation has claimed not just structures, but also human lives. Some initial studies on the nature of fires have been performed from orbit; however, these results are neither real time nor high resolution. [1,2,3,4,5,6] Thus, they cannot be used to assess fire in-progress, and, much less, to determine the fire front location and direction of fire propagation to assist in the fire management actions.

People have moved their technologies and structures closer to the fire's natural habitat. However, they have failed to bring along the requisite diagnostic (infrared) technology to assure close and safe co-existence with a remarkable opponent: the fire. The basic fire-fighting strategies have not changed since the sixties. Limited technological resources are used for fire wild-fire monitoring.[7] More and more studies also propose unmanned air vehicles for wildfire observation, incorporating even the simplest IR devices. [8,9,10,11]

We studied fire propagation for domestic and industrial applications, to assess its initiation and evolution, with a particular emphasis on safety considerations.[12,13] Studying a home burner both in visible and in IR, we observed, for example, that the spark plug functioned to heat the air around it, rather than to heat the fuel, in the initial incorporation of the device. This resulted in a dangerous accumulation of fuel. The challenges of fire research include development of

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instrumentation detecting events with simultaneously high spatial and high temporal behaviors. We believe that sophisticated state-of-the-art infrared imagers could be deployed to give fire-control managers the advantage necessary for damage-free fire subjugation. An agile air-vehicle, with human crew due to the fire unpredictability and need for large field of view, would carry observational equipment, sensible in IR carbon dioxide bands.

We study the propagation of a recent fire that started when a lightening struck a bush in Arizona high desert in a hot afternoon. There were approximately 15 other fires in the State of Arizona within the 24 hours of the start of the Yarnell Hill Fire (TYHF), and 5 other small fires, also caused by lightening. All of them were soon controlled. A large percentage of natural fires are easily controlled, while a few turn into major catastrophes. TYHF lingered initially, and finally flared with incredible speed and energy. This fire has been analyzed and documented in great depth, providing potentially most accurate information about any fire event as yet. Our data comes from these reports. [14,15,16]

2. DATA AND METHODOLOGY

We examine the temporal evolution of TYHF hoping to identify its differentiating features. This fire burned southwest (SW) of Prescott, Arizona, June 28 – July 10, 2013, with reported property damages of 5.5 M$, 19 firefighter casualties, and undisclosed costs associated with fact-finding and damage compensations. Our information about this fire has been obtained from these studies [14,15,16] and visual inspection of terrain afterwards. In these reports, events were reconstructed upon interviews with fire-fighting staff and management, recorded communications, and logs. Figure 1 shows the geographic map of the fire region: the fire perimeter is indicated as a red circle.

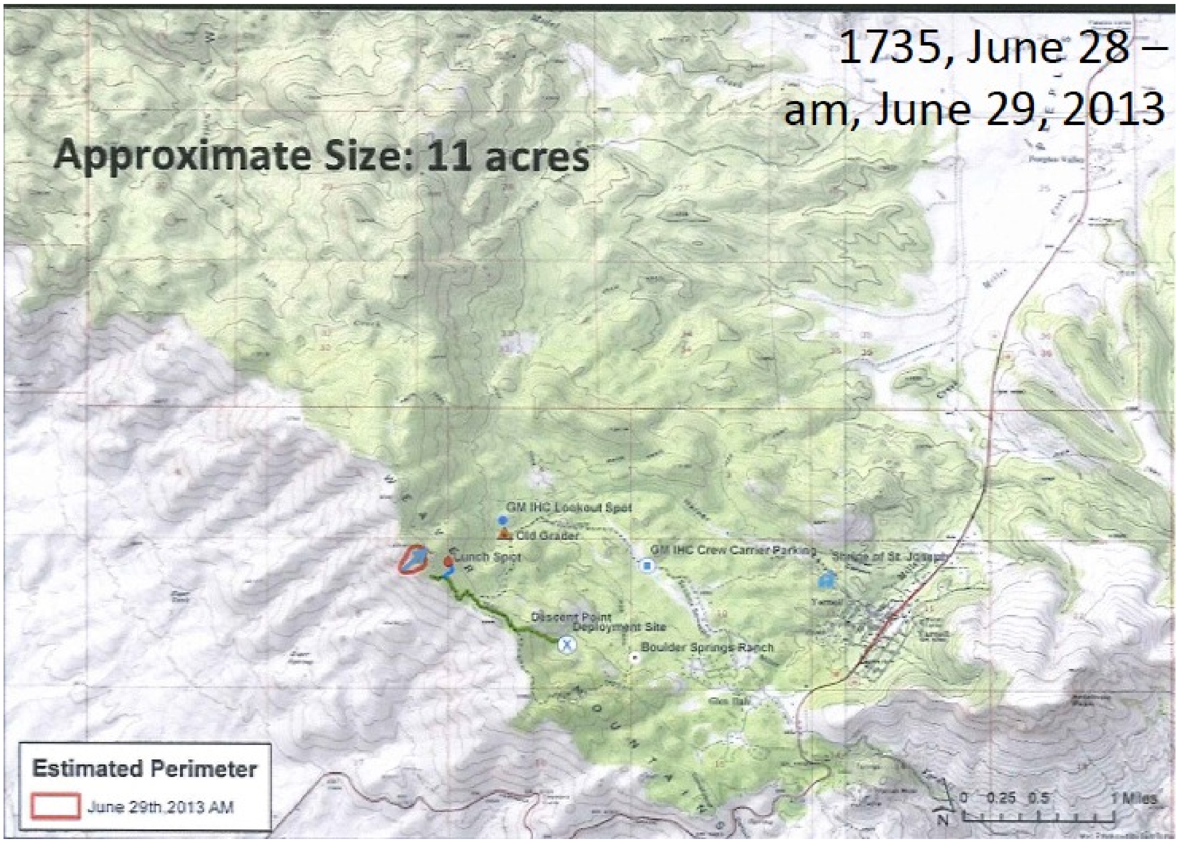

Fig. 1. The fire grows to about 11 acres during the 16 hours after it has started.

We are interested in determining how the fire propagated in general, and what was the fire-front evolution as a function of time, during the first 45 hours when the ranging fire turned around and gave rise to a pyrocumulonimbus cloud. Reference 16 provides a set of maps, delineating the extent of fire 12 times during this interval, with higher frequency when the fire was perceived to propagate more rapidly. We use military time for clarity, although occasionally data is available only as morning or "am", as the best information. Each figure includes the scale in the lower right corner, with about 1 in = 1 mile.

The nearly straight line at about N-NE on the right side of each map is AZ State Freeway 89, passing through the city of Yarnell (lower right, 3 mi SE from the initial fire site) and Peeples Valley (upper right, 3 mi NE). The seasonal wind for this locality is toward N-NE direction, corresponding to the direction of the valley and the freeway. The first city gave the name to this fire that actually starts near a 6,000 ft peak in the Weaver Mountains. The fire grows to 113 acres within the initial 24 hours (see Fig. 2). We do not completely adhere to the fire-fighting terminology. There are two reasons for it. First, we are new to this area of expertise and ignorant. Second, our ignorance allows us to question basic premises in this area of expertise, allowing us to identify potential inconsistencies held dear to this specialty.

We define the fire-front the same way as wave front is defined in optics. The fire perimeter at time t_2 (t_1) defines the fire-front at time t_2 (t_1). Figures 1 through 11 show the fire perimeter (in red) at two consecutive times when the fire extent is actually known. Also, the cartographic shading is presented in the original data with top-left lighting, and low-visibility contours, on an earlier geographic map. The fire perimeter is drawn for each time separately, with fire extent indicated on upper left side. Some key locations are indicated that allow us to superimpose two such consecutive maps. The second map in time in superimposed with a 50 % transparency. Imperfect superposition in some instances gives an incorrect impression of defocus. In the upper right corner, we indicate the two times bounding the period of fire is expansion. We only have information about the fire-front location at two consecutive times.

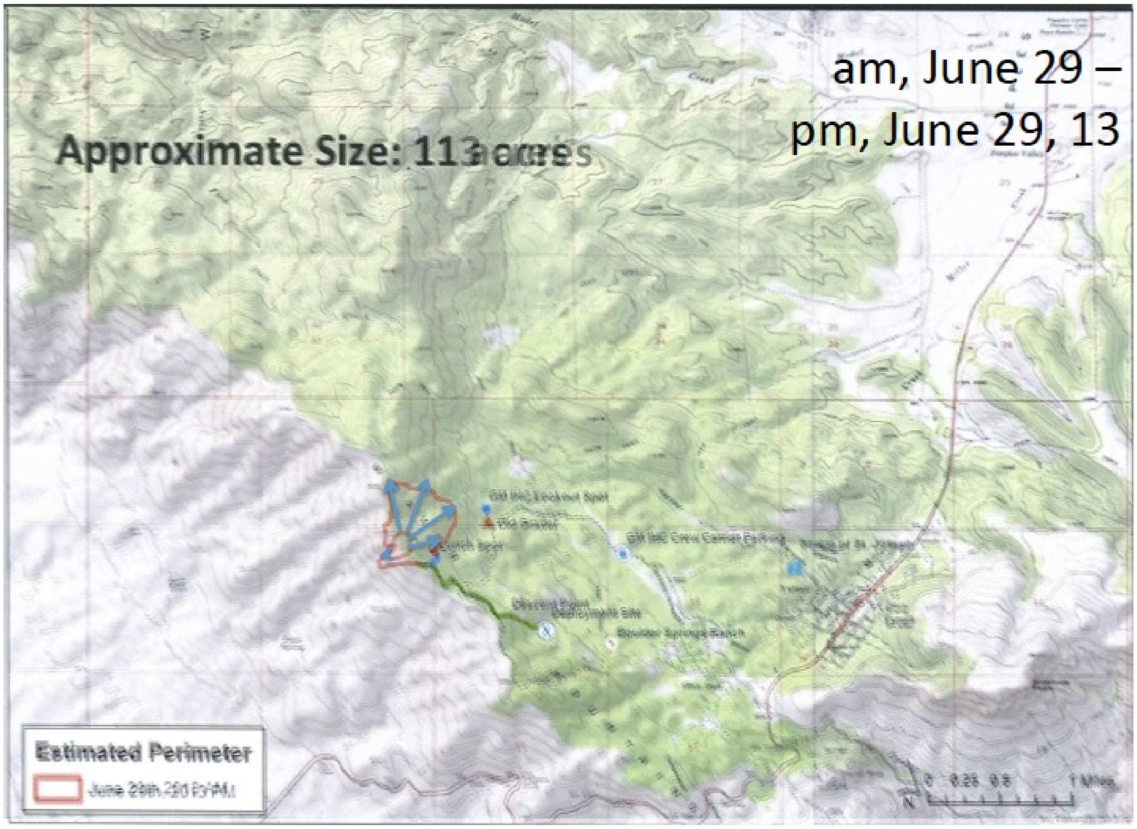

Fig. 2. The fire grows to 113 acres within the initial 24 hours.

The fire front can theoretically move just about in any direction where fuel, oxygen and heat is available, i.e., it can change direction every instant of time. (Fuel refers to underbrush and low moisture /dry vegetation.) The wind favors fire propagation along the wind direction, assuming there are fuel and oxygen available. From the combustion point of view, the wind's contribution is to bring heated air inside the combustion volume, thus facilitating the ignition.

3. FIRE EVOLUTION

Here we make the first assumption, in the absence of other information. We assume that at time t_2 the fire perimeter is indeed the fire front and that fire propagates normally to the fire perimeter at time t_2. This allows us to connect fire perimeter at time t_2 with fire perimeter at time t_1 with a line perpendicular to fire perimeter at time t_2. These blue lines are indicated with an arrow in Fig. 1 through 11, covering the space between two perimeters. One mile is indicated as a horizontal line in the lower right corner. The area of fire growth in these figures is thus indicated in blue. The longest blue line in each figure determines the fire-front (maximum) magnitude; and its division by elapsed period provides fire front velocity. We choose to associate the velocity of fire propagation with the fire perimeter at time t_2, rather than half way between both perimeters to incorporate real data whenever possible. We emphasize again that if the fire spreads in a zigzag fashion, its instantaneous velocity might be much higher in magnitude and variable in direction.

TYHF starts with lightening near the top of the Weaver Mountain SW of Prescott, and NW of Phoenix, Arizona, on June 28, 2013, at 5:30 pm, reported by observers in Congress, a small city 5 mi SW from lightening site. Arrows in Figs. 1 through 11 show how the fire propagated in temporal intervals, noted in the upper right corner. We see that fire direction of the fire front propagation changes in an unpredictable manner.

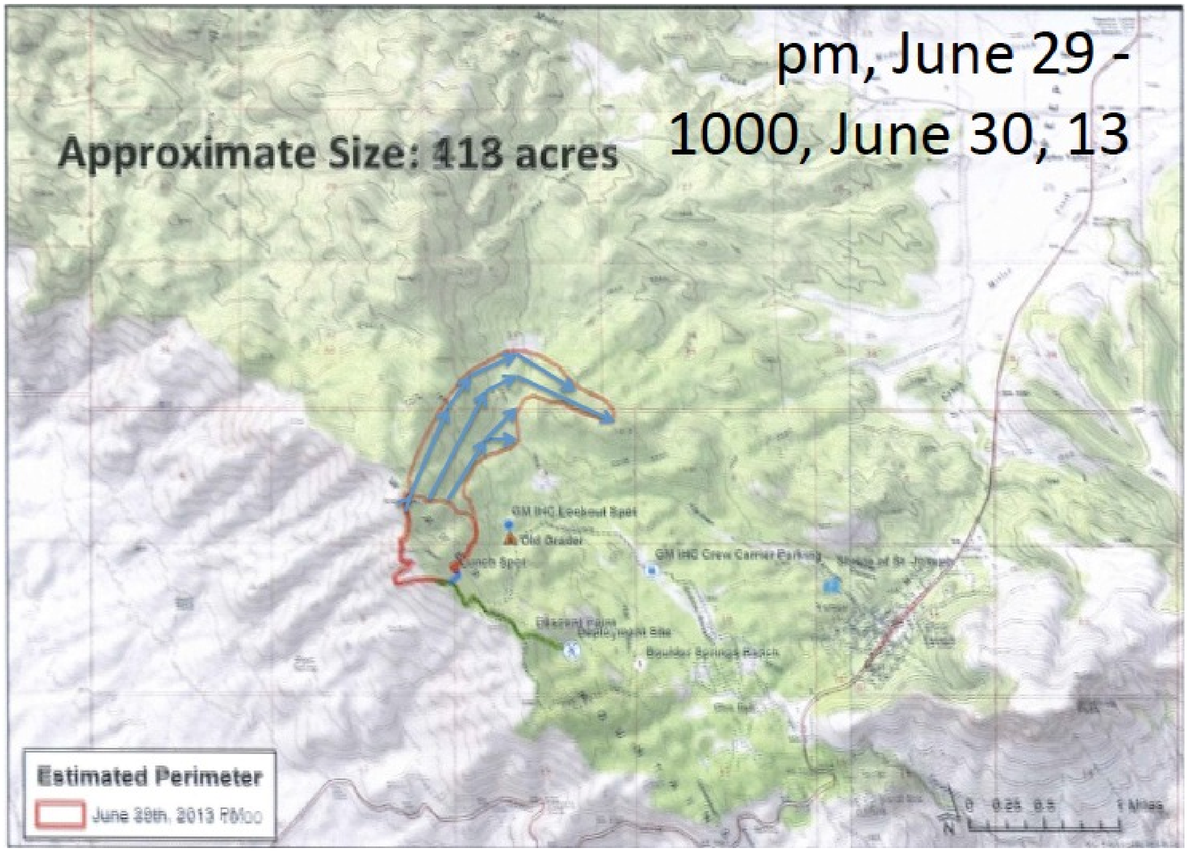

Fig. 3. Fire continues burning through the night. In the morning, it changes direction toward E-SE.

The first two figures indicate that the fire is evolving relatively slowly during the first evening. Figure 3, however, shows that the fire continues speeding in the N direction through the night. In the early morning, it changes direction toward E-SE. Decreased wind activity, lower temperatures and increased humidity characterize nights in Arizona. These factors favor a decrease in the speed of fire propagation. The fire nighttime-early morning eastward expansion establishes a wide stretch of the fire front, illustrated in Figs. 3 and 4.

From around 1300 on, the fire propagates eastward again, along the ridges sloping down gently along the same direction (eastward). The wind toward N-NE continues during another hot AZ afternoon at 101 F (35 C). This is shown in Fig. 5. At approximately, 1530 pm – 1545 pm, the wind abruptly changes direction westward, to W-NW (change of 90^o). This is a precursor wind from the storm south of Prescott (NE of the fire). This wind reverses the direction of fire front propagation from toward E-NE to S-SE (also change of 90^o), presented in Fig. 6. The hot air from earlier combustion is pushing over the previously burnt areas. The air is charged with heat. This means that valleys that fire previously has passed over are now also igniting.

We emphasize that wind was reported in NW direction and SE direction during the same 15-minute time interval, the first one reported by ground personnel on the SW fire perimeter and the second one was relayed. It was predicted by the National weather service and then reported on ground by different observers. This discrepancy gives rise to the hypothesis that local microclimates might be established in a mountainous fire environment.

Flanking fire along E-SE direction becomes a fire head, staring at about 1600, as seen in Figure 7. The outflow boundary from the Prescott storm nears the N edge of the fire in direction toward S-SW with speeds of 16 mi/hr, pushing the hot air and the fire back onto itself. At about the same time, the National Weather Service in Flagstaff (N) issues an advisory to expect outflow (boundary) winds in direction S-SW from the storm in Prescott with wind speeds of 35-40 mi/hr.

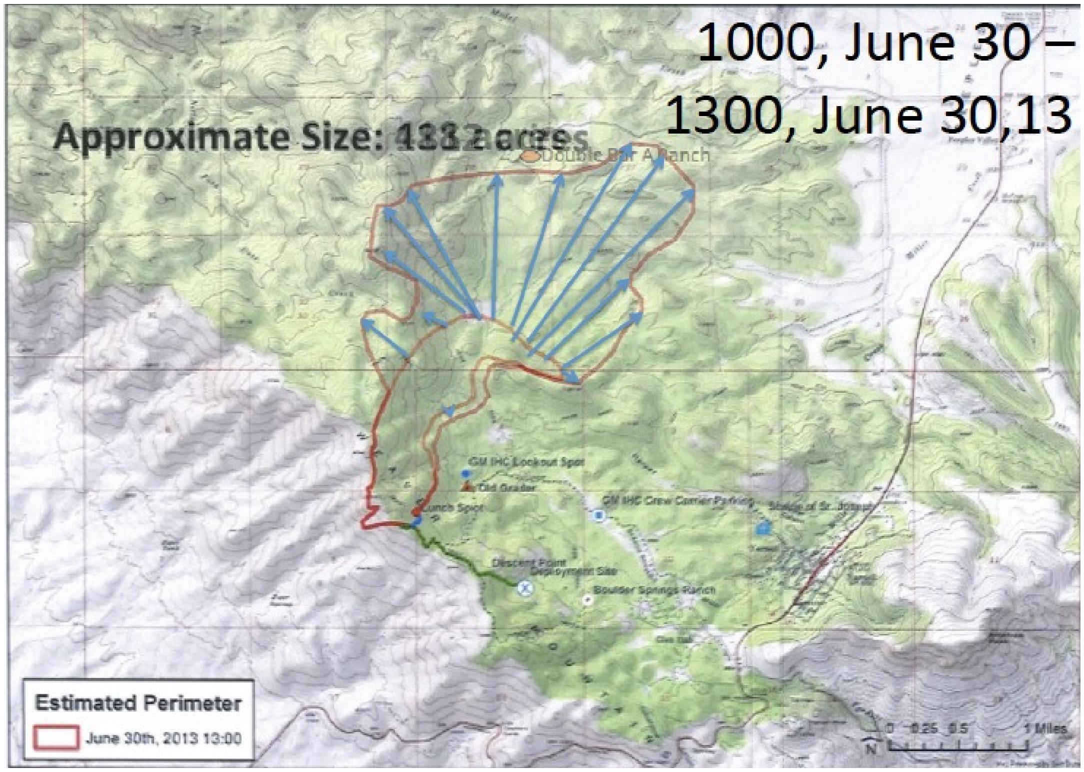

Fig. 4. The fire starts to propagate N, N-NW, N-NE from the wide fire front during the midday heat.

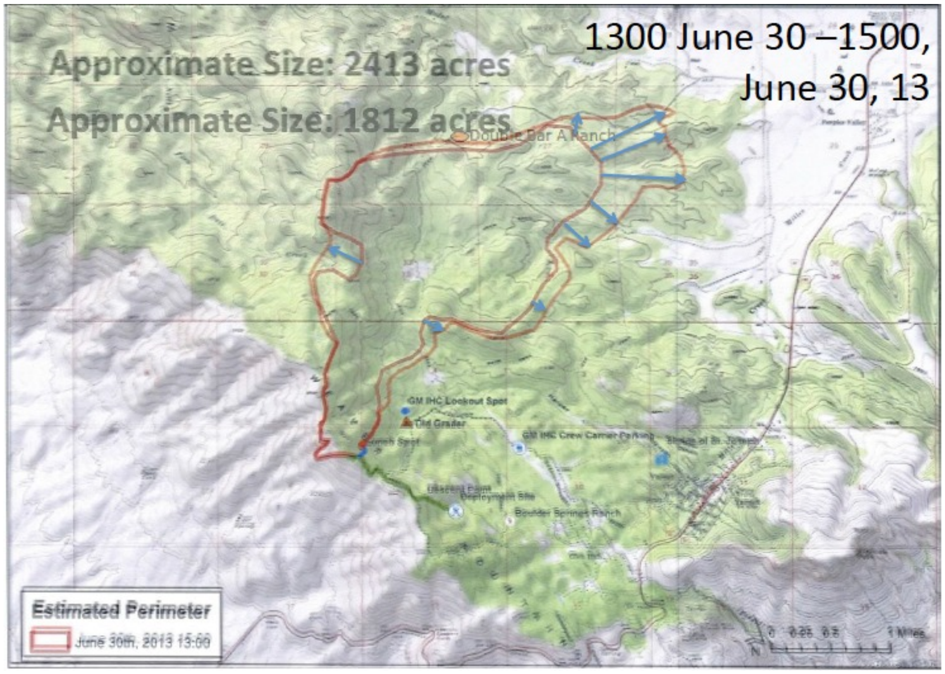

Fig. 5. The fire propagates eastward again, along the ridges sloping gently along the same direction.

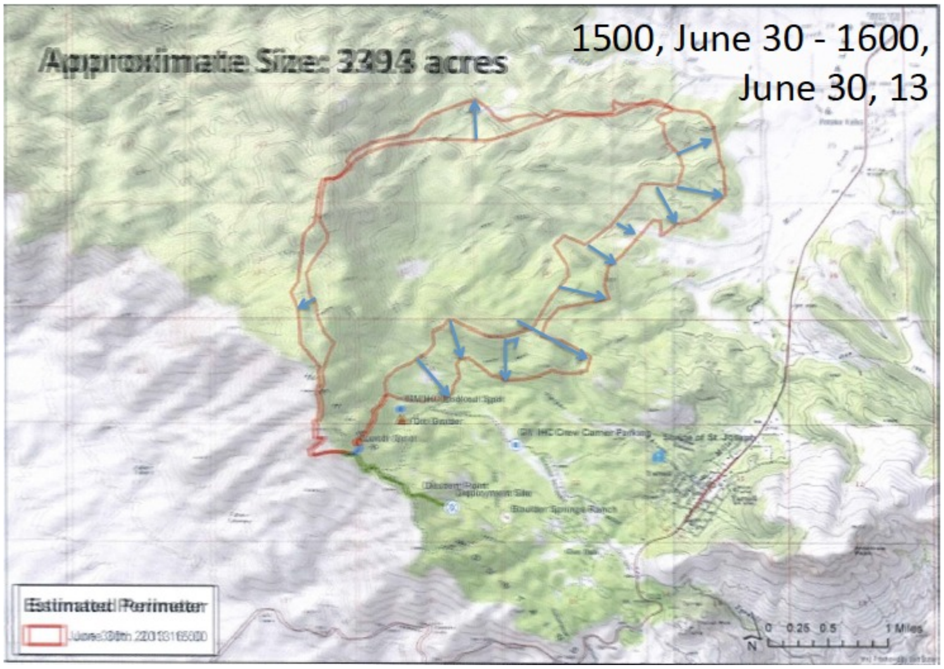

Fig. 6. The fire front changes direction toward S-SE starting at about 1500, due to wind change.

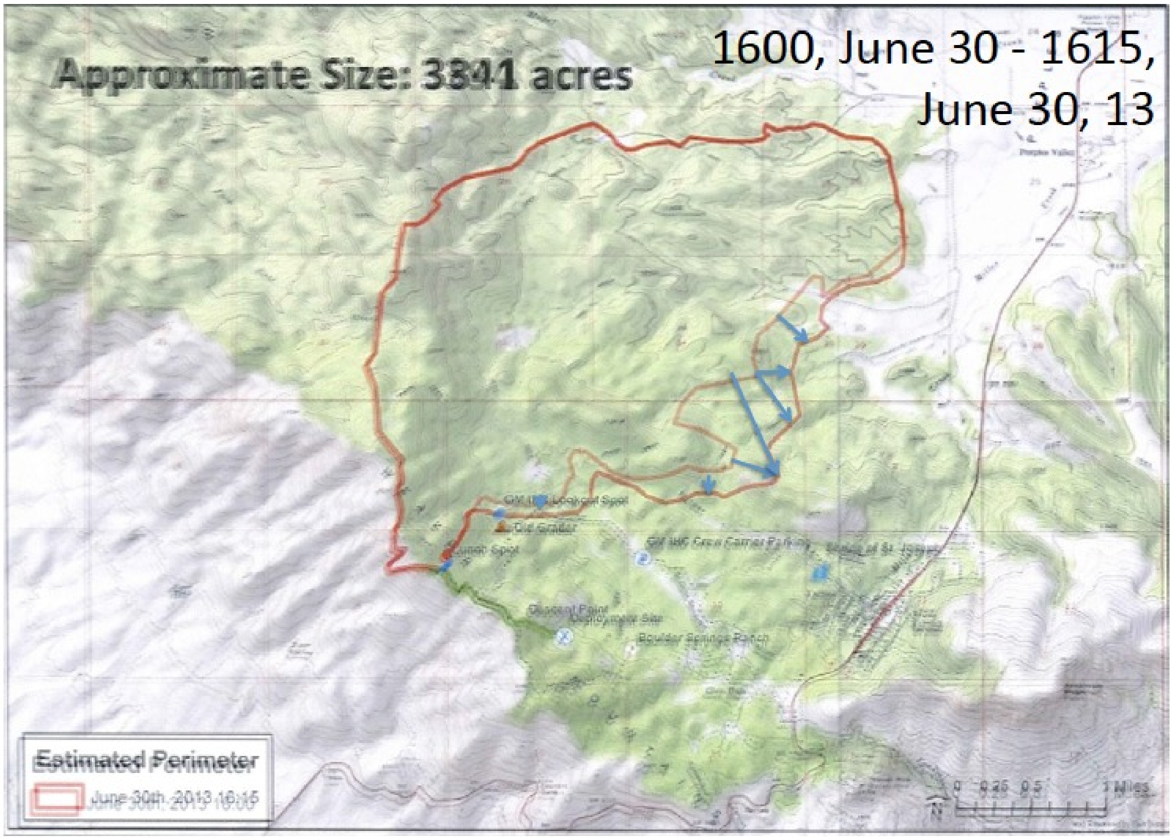

Fig. 7. Flanking fire along E-SE direction becomes a fire head at 1600.

At 1630 pm, the outflow boundary moves across the S edge of the fire, pushing the fire front primarily in SE direction. The wide fire-front is actually ranging from S to E perimeter of fire. This may be clearly appreciated upon examining Fig. 8. The reported positions of the outflow boundary layer indicate its speed of 35 mi/hr.

From 1630 to 1640, the outflow boundary is moving at 35 to 40 mi/hr in S-SW direction. The E front of the fire is just closing some gaps where the fire has not yet propagated. The fire perimeter is approaching a circular shape, according to Fig. 9. The wind direction continues toward S-SW. On the SW corner of the fire, there are two ridges that roughly run perpendicular to the outflow wind S-SW direction. These ridges momentarily detain the fire front propagation along the outflow direction. The fire moves along the ridge along the iso-contour, until it encounters an opening in the ridge profile.

At 1640, the fire perimeter enclosing the burnt area is nearly circular. Then, it propagates at 1640 from behind the first ridge and at 1650 from behind the second ridge. Figure 10 illustrates this regular circular shape where fire has finally closed upon itself and it is burning near to its starting point.

The outflow boundary continues in S-SW direction at 35 to 40 mi/hr. Fire propagates normal to the long S-SE fire perimeter in S-SE direction at 1700. The Weaver Mountain ridge delineates the fire boundary at W to SW fire perimeter.

The fire-front direction and speed of propagation is shown in Fig. 12 for each known time. The length of the arrow represents the fire-front vector displacement in the interval bounded by times at the beginning and end of the arrow. The fire head moves along distinct positions on the fire perimeter, ending within yards of the fire initiation. The arrows are connected head to tail for temporal continuity and to exhibit roughly the rotational nature of this fire propagation.

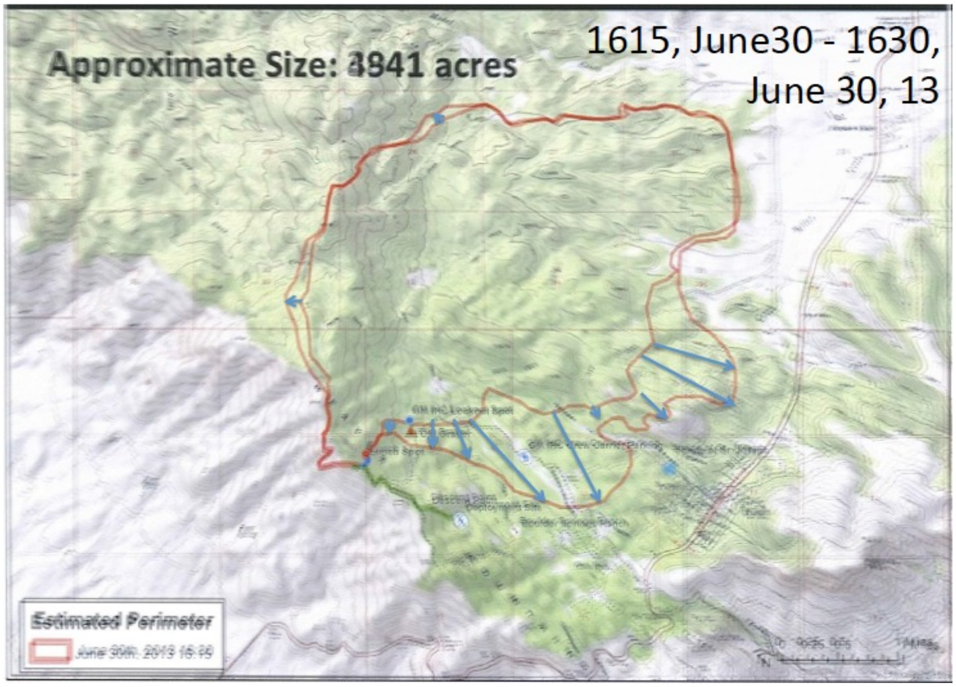

Fig. 8. The wide fire-front is ranging from S to E perimeter of fire at 1630.

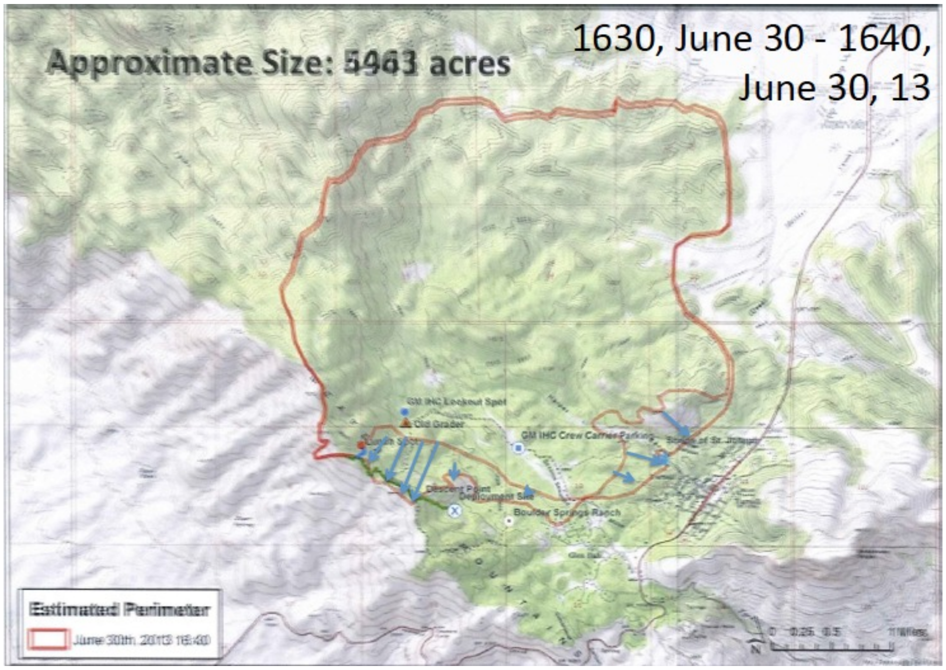

Fig. 9. The SE and SW fronts of the fire are just closing some gaps between 1630 and 1640. The fire perimeter is assuming a circular shape.

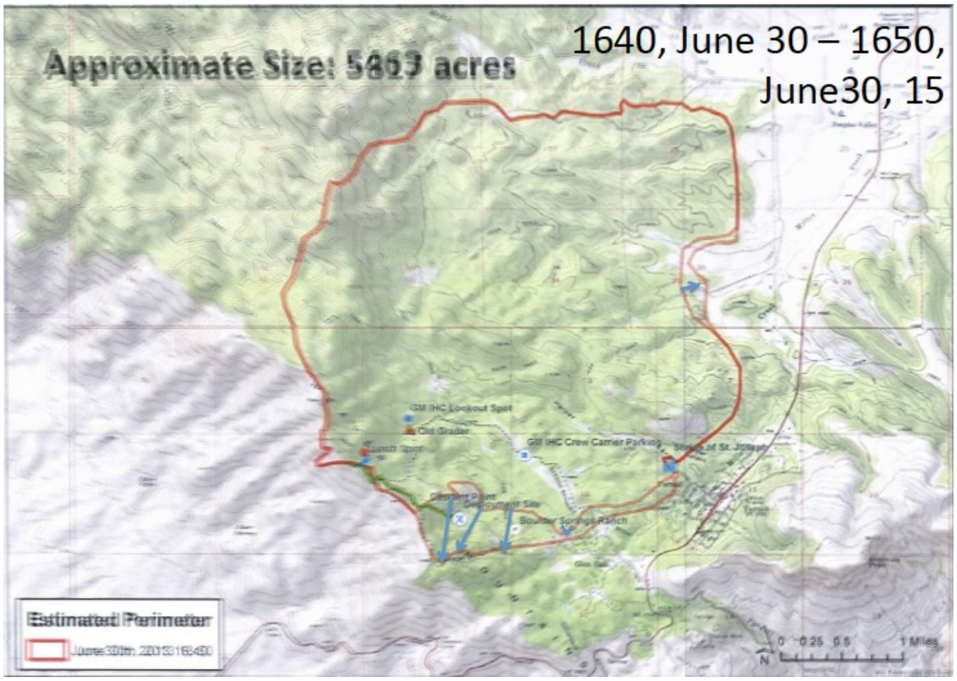

Fig. 10. The fire front propagates from behind the second ridge in S direction at 1650.

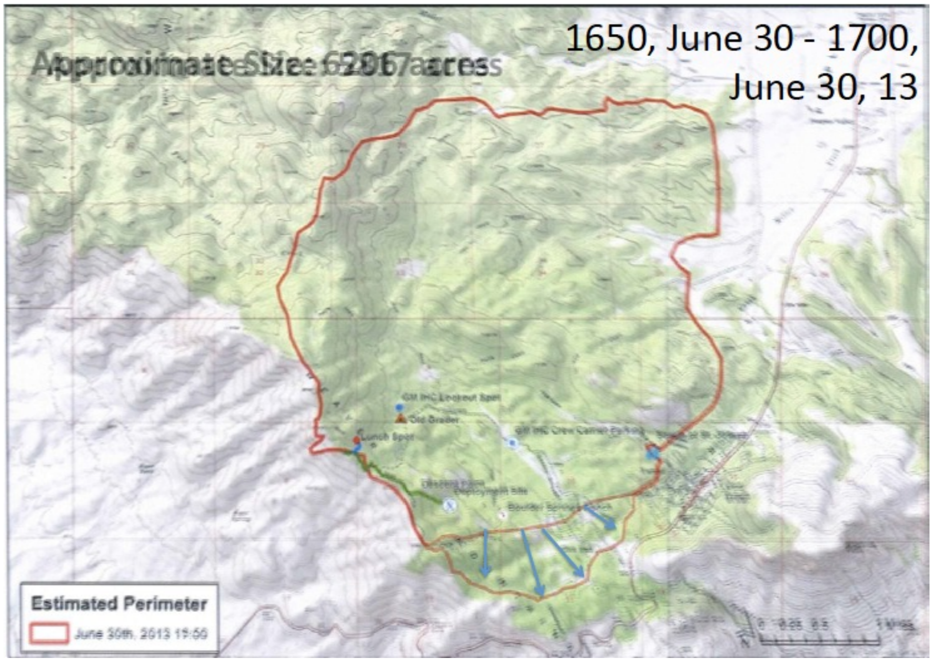

Fig. 11. Fire propagates normal to the long S-SE fire perimeter in S-SE direction at 1700.

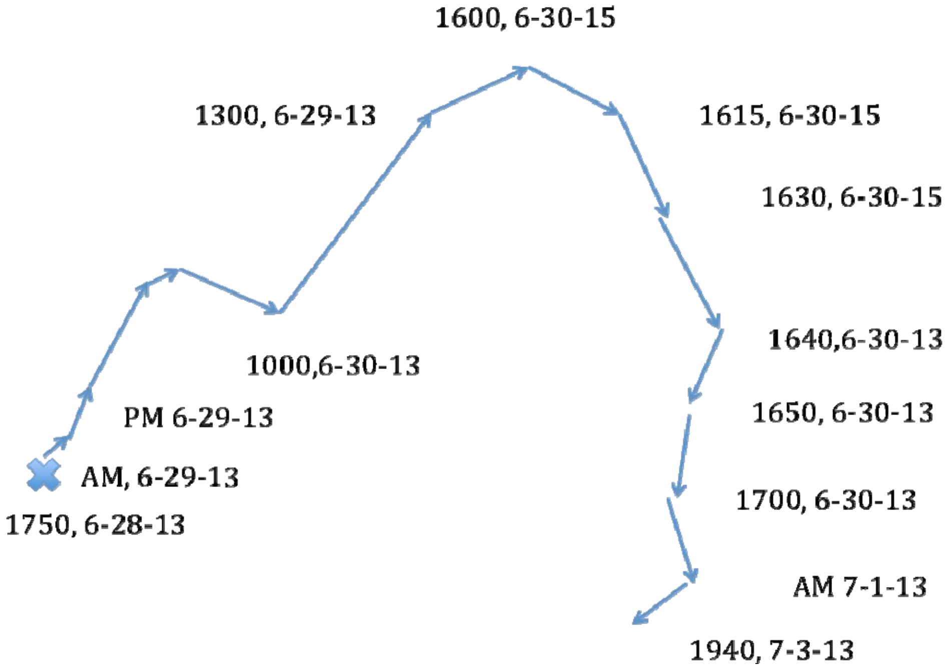

Fig. 12. The maximum fire-front magnitude and its direction of propagation is shown for each known time (in military time, followed by date according to the US convention), from Figures 1 through 11). The arrows are connected for temporal continuity. The fire head moves along the fire-front throughout the fire evolution, turning direction by 180 °.

4. CONCLUSIONS

The propagation pattern of this fire appears to move first from S-SW direction to N-NE, reversing its direction at about 35 hrs after the lightening strike. Upon further analysis, we observe that the direction of fire front follows a nearly circular motion, with the significant acceleration during the last five hours of the intense fire. Such behavior qualifies it as a complex fire.

We see that fire direction of the fire front propagation changes in an unpredictable manner. This inspires us to propose that different areas within fire perimeter subject to different microclimates.

Procedures need to be developed to recognize complex fires prior to their explosive behaviors. A fire-monitoring plane would perform reconnaissance encircling from a safe side distance from the fire perimeter. It would require human control to respond to rapidly changing environmental and combustion conditions. It would easily incorporate a bispectral IR imager, possibly with large field-of-view and higher than TV frame rates. A sequence of fire images would indicate whether the fire exhibits significant amount of turbulence, vortices, vertical buoyancy and diverse micro-climatic environments. It would provide immediate situational observations to managers controlling the ground forces and air defenses (administration of fire retardant and water deliveries).

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